Energy Loss of High P_{T} Partons

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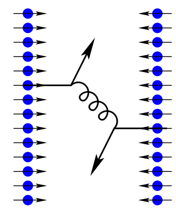
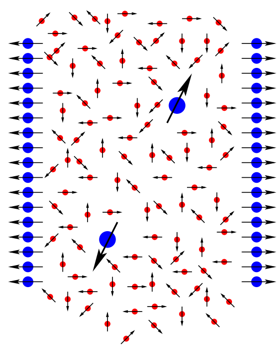
- Overview and Review
- The approach
- The calculation
- Results: suppression of jets, with respect to pp, is nearly energy independent
- What remains to be done

Physical picture

primary partons collide to give (rare) hard partons.



Hard partons must punch out through QGP.



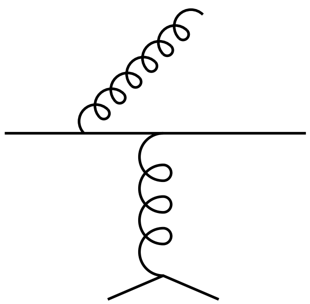
Energy loss along the way means that, on hadronization, the produced hadrons are lower energy than they would have been in a pp collision.

Energy Loss I

Energy loss to binary collisions Does Not Increase as parton's energy increases!

—Less important for hardest partons

Main energy loss is by Bremsstrahlung radiation



Naively, energy loss rate

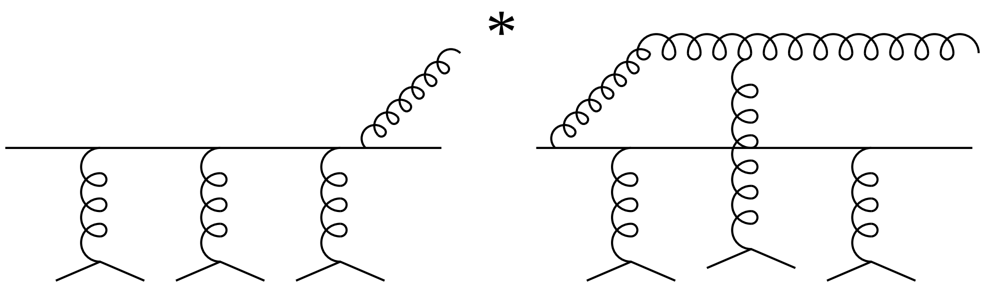
$$\frac{dE}{dx} \propto E$$

due to growing phase space for the final bremmed gluon

Energy Loss II

Bremsstrahlung dominates – but it is complicated!

QGP is a dense medium and bremsstrahlung has a long formation time. Emission amplitudes for successive scatterings can interfere:



Low densities: large random phases kill interference terms

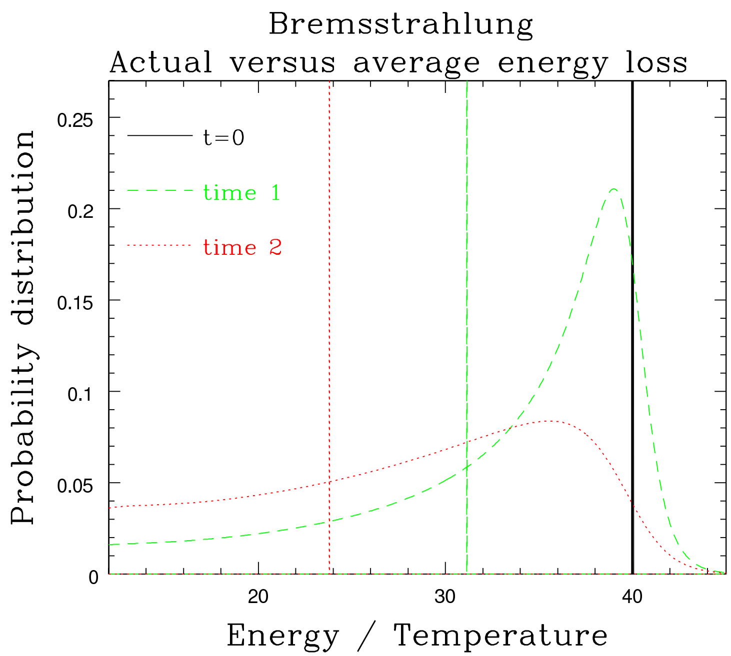
High densities (QGP): interference effects are $O(1)$.

The LPM effect!

Energy Loss III

Bremsstrahlung: energy loss dominated by rare, large E loss events.

A mono-energetic sample, undergoing brem, ends with a broad range of energies.



This is very important for a *steeply falling* initial spectrum–as occurs for hard jets!

Extreme Example

Imagine a spectrum, $dN/d^2p_\perp \propto p_\perp^{-10}$.

Suppose an energy loss mechanism such that half of particles lose all their energy, half lose nothing.

–Spectrum suppressed by a factor of $1/2$.

The average loss was $\frac{1}{2}$. If every particle had suffered the average loss instead,

–Spectrum would be suppressed by 2^{-8}.

Using the averaged energy loss can be *very wrong*

Our goal

Revisit calculation of energy loss, taking care to

- evaluate bremsstrahlung rate at leading order in α_s
- treat the LPM effect in a complete way
- include medium effects
- treat correctly the evolution of the spectrum

LPM modified bremsstrahlung

Multiple scatterings require resummation over an infinite set of diagrams, very similar to diagrammatic derivation of Bethe-Salpeter or Boltzmann equations.

Basically done correctly by Baier *et. al.* modulo a few details:

- dynamic, rather than static, scatterers
- medium corrections to dispersion

Neither improvement on Baier *et. al.* treatment is significant.

Bremsstrahlung rate is

$$
\begin{aligned}
\frac{d\Gamma(p,k)}{dk\,dt} &= \frac{C_s g_{\rm s}^2}{16\pi p^7} \frac{1}{1 \pm e^{-k/T}} \frac{1}{1 \pm e^{-(p-k)/T}} \times \\
&\times \left\{ \begin{array}{cc} \frac{1+(1-x)^2}{x^3(1-x)^2} & q \rightarrow qg \\ N_{\rm f} \frac{x^2+(1-x)^2}{x^2(1-x)^2} & g \rightarrow qq \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g \rightarrow gg \end{array} \right\} \times \\
&\times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h} \cdot \mathrm{Re}\, \mathbf{F}(\mathbf{h},p,k)\,,
\end{aligned}
$$

(p: primary energy; k: gluon energy; $x \equiv k/p$;
$\mathbf{h}$: measure of non-collinearity)

Here $\mathbf{F}$ is given by

$$
\begin{aligned}
2\mathbf{h} = \;& i\delta E(\mathbf{h},p,k)\mathbf{F}(\mathbf{h}) + g^2 \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} C(\mathbf{q}_\perp) \times \\
& \times \Big\{ (C_s - C_\mathrm{A}/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h}{-}k\,\mathbf{q}_\perp)] \\
& \quad + (C_\mathrm{A}/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h}{+}p\,\mathbf{q}_\perp)] \\
& \quad + (C_\mathrm{A}/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h}{-}(p{-}k)\,\mathbf{q}_\perp)] \Big\}, \\
\delta E(\mathbf{h},p,k) \;&= \frac{\mathbf{h}^2}{2pk(p{-}k)} + \frac{m_k^2}{2k} + \frac{m_{p-k}^2}{2(p{-}k)} - \frac{m_p^2}{2p} \,.
\end{aligned}
$$

with $C(\mathbf{q}_\perp) = \frac{m_\mathrm{D}^2}{\mathbf{q}_\perp^2(\mathbf{q}_\perp^2 + m_\mathrm{D}^2)}\,, \quad m_\mathrm{D}^2 = \frac{g_\mathrm{s}^2 T^2}{6}(2N_\mathrm{c} + N_\mathrm{f})\,.$

Red: differences WRT. Baier *et. al.*

Expression for $\mathbf{F}(\mathbf{h})$ was an integral equation. Two solution methods:

- Brute force
- Approximation that LPM effect is large

Doing the calculation: LPM effect is a factor of 2 suppression for $k = 10T$ (T the plasma temp, k the emitted gluon energy) and smaller for smaller k.

Steeply falling spectrum: $k \ll p$ are most important (a particle, losing just part of its energy, is buried under more common particles of that energy)

One Must Use the Brute Force Approach!

Evolution of hard parton distributions

Quark, momentum p, emits gluon, momentum k: $N_q(p)$ drops, but $N_q(p-k)$ and $N_g(k)$ increase. Joint evolution equations:

$$
\begin{aligned}
\frac{dP_q(p)}{dt} &= \int_k P_q(p{+}k)\frac{d\Gamma^q_{gg}(p{+}k,k)}{dkdt} - P_q(p)\frac{d\Gamma^q_{gg}(p,k)}{dkdt} \\
&\qquad + 2P_g(p{+}k)\frac{d\Gamma^g_{qq}(p{+}k,k)}{dkdt}\,, \\
\frac{dP_g(p)}{dt} &= \int_k P_q(p{+}k)\frac{d\Gamma^q_{qg}(p{+}k,p)}{dkdt} + P_g(p{+}k)\frac{d\Gamma^g_{gg}(p{+}k,k)}{dkdt} \\
&\qquad - P_g(p)\left(\frac{d\Gamma^g_{qq}(p,k)}{dkdt} + \frac{d\Gamma^g_{gg}(p,k)}{dkdt}\Theta(2k{-}p)\right)
\end{aligned}
$$

Weaknesses of Approach

- Assumes QGP is thermalized
- Perturbative treatment: how reliable is leading order in α_s?
- Treatment assumes formation time short compared to propagation time
- Treatment assumes formation time short compared to time between bremsstrahlungs

The last 2 are consistent with α_s expansion (if enough energy loss occurs to be interesting)

Incomplete and In Progress

- $2 \leftrightarrow 2$ (Binary) processes
- Nuclear geometry
- Hydrodynamic development
- Hadronization: hard partons to high energy hadrons

So far: evolution through a finite slab

Assumed initial $p_\perp$ spectrum: $dN/d^2p_\perp \sim (p_\perp^2 + p_0^2)^{-5}$ with $p_0 \sim 1.75$ GeV [Wang and Wang]

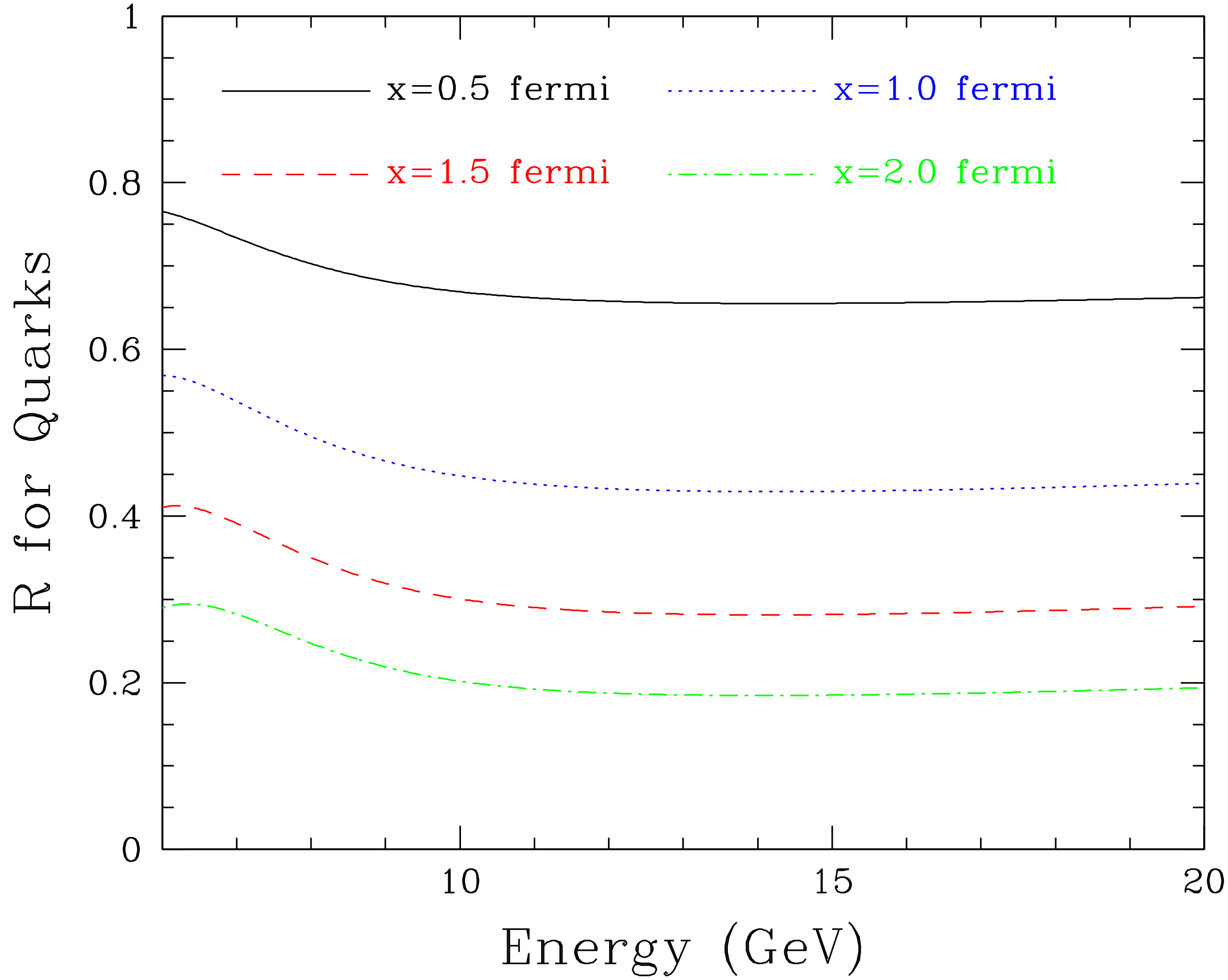
Result scales: Energy loss, writing E/T (T the temperature) and $x \times g_s^4 T$ (x the slab thickness), is "pure" result.

For presentation, we take $T = 400$ MeV, $\alpha_s = 1/3$

Plotted quantity:

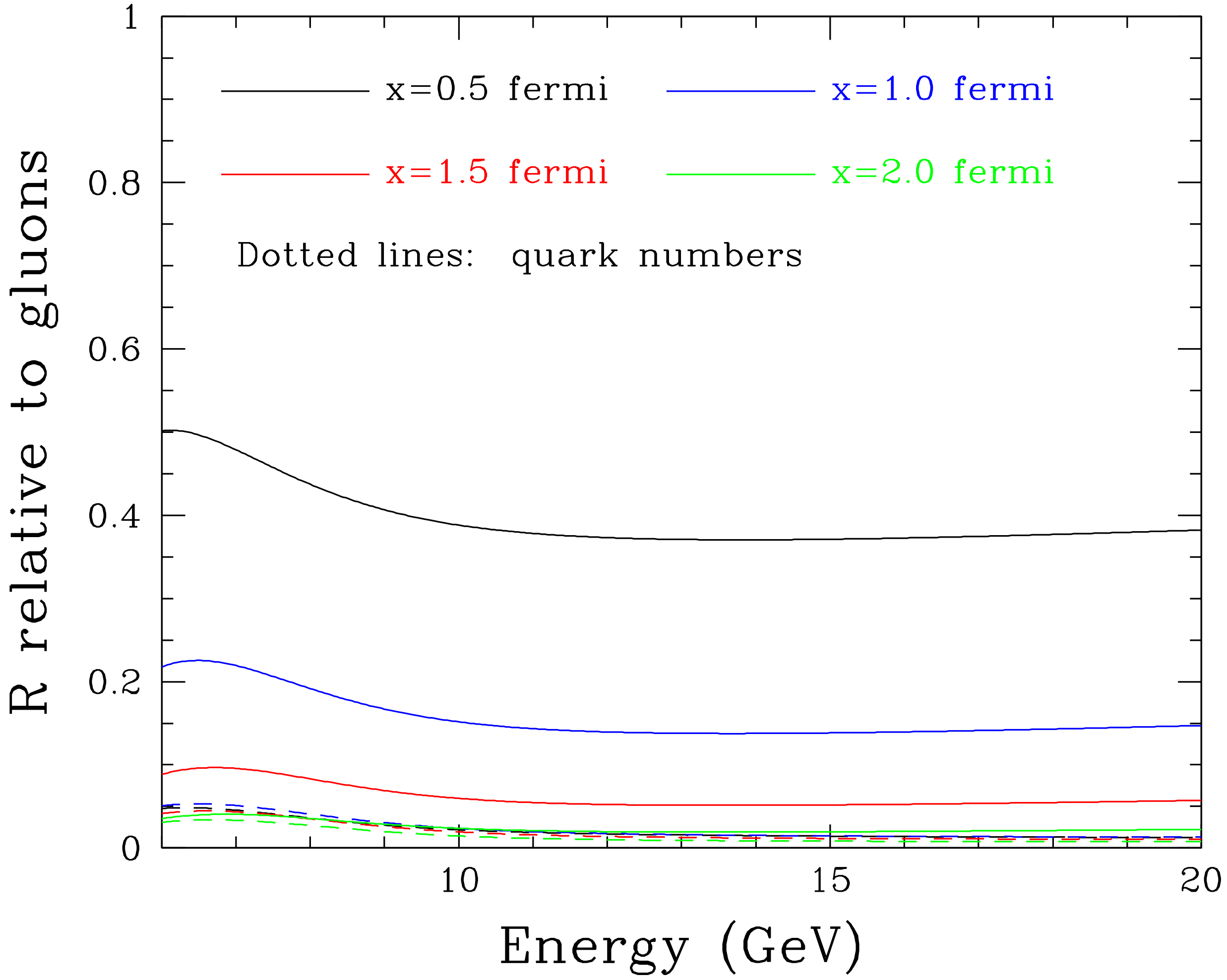
$$\tilde{R} \equiv \frac{\text{Final } dN/dp}{\text{Initial } dN/dp}$$

Initially Pure Quark Spectrum



Negligible glue produced.

Initially Pure Gluon Spectrum



Gluons lost more than twice as fast as Quarks

Results so far

- Falling ratio
$$\tilde{R} \equiv \frac{\text{Final } dN/dp}{\text{Initial } dN/dp}$$
becoming flat around $20T$ (8 GeV?) and remaining flat out to quite high energy > 20 GeV

- assuming same initial population of hard partons, the same will hold for
$$R \equiv \frac{\text{AA } dN/dp}{\#\text{ collisions } \times \text{ pp } dN/dp}$$

- Gluon energy loss twice as fast as quark energy loss

Conclusions

We still need to include nuclear geometry, but

It is difficult to see how central result–very flat $\tilde{R}$–could change.

Initial state effects (Cronin, shadowing) not needed to explain $p_\perp$ independent suppression of high $p_\perp$ hadrons.

We expect the same flat behavior at the LHC.

It should be easy to extend this work to γ production by hard partons traversing the QGP.